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Title: AUTONOMOUS POWER SYSTEM FOR REMOTE LOCATIONS

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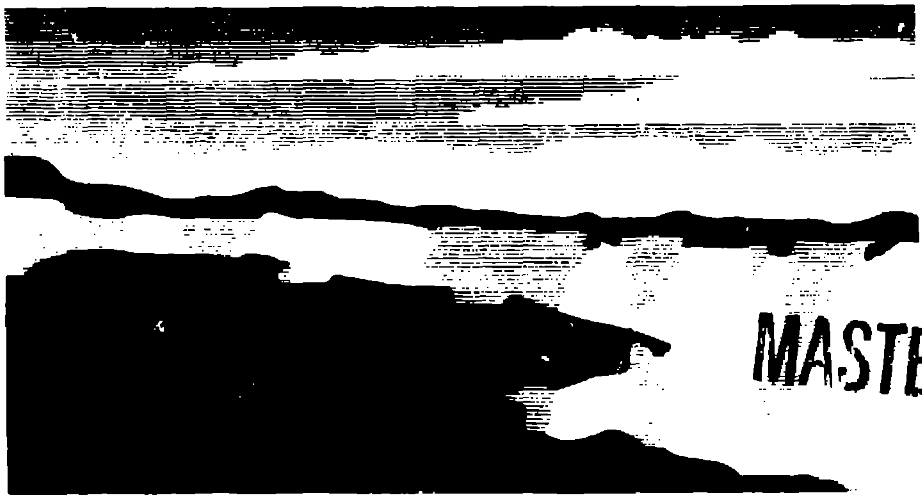

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AUTONOMOUS POWER SYSTEM FOR REMOTE LOCATIONS

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Abstract

The Russian technical specialists of Krasnaya Zvezda (Red Star) and Kurchatov Institute of Atomic Energy (KIAE) of Moscow were tasked in the early 1970's to develop a compact, transportable power system that would work reliably and autonomously at remote locations. The original system specifications required that it be able to operate for several years without maintenance in sea water at a depth of 6 km. To meet these requirements the Russia specialists designed a compact nuclear system with water coolant coupled to a thermoelectric power conversion subsystem. The goal was to design a system that was scalable from 300 kWth to 300 MWth.

A proof-of-principle system, the GAMMA reactor system, was designed, constructed and tested at KIAE. The system construction was completed in 1981 and testing began the same year. The GAMMA reactor system is still operational today. The follow-on system for remote sites is the ELENA reactor system. It has not been built, but the final assembly drawings have been completed and are ready to be used. The ELENA was designed to provide both direct electric power and local space heating. It can also be used for desalination. The design of the ELENA meets post-Chernobyl safety requirements and includes features to assure its safety under autonomous operation. This paper provides an overview of the GAMMA and ELENA power systems including their design criteria, testing, and transportation to remote sites. And includes discussion on an evaluation and technology transfer program that could make this system available for use throughout the world.

Introduction

The Russian technical speciali ts at Krasnaya Zvezda and Kurchatov Institute of Atomic Energy (KIAE) have designed and tested a prototype of a compact, transportable power system that works reliably and autonomously at remote locations. The GAMMA reactor system is the prototype that has been built and tested at KIAE. The GAMMA was designed as a proof-of-principle unit for an undersea power plant. The follow-on system, the ELENA, has been designed for operation at remote sites to provide power and local heating. The assembly drawings of the ELENA have been completed, and are ready for fabrication and testing of the system. The ELENA system was designed with inherent safety features to ensure it remains in a safe configuration under any condition.

This paper provides an overview of the GAMMA reactor system and its operation, the design requirements for the ELENA reactor, and a discussion of the technology transfer program that could make this system available for use throughout the world.

GAMMA Reactor System

In the early 1970's the Russian specialists were tasked to develop a highly reliable power source that could operate within the ocean to a depth of 6 km for several years without field service. The primary design principles of the GAMMA reactor system were:

1. natural circulation and self-regulation of the reactor and secondary coolant loops,
2. an inherent negative reactor temperature coefficient,

3. steady-state reactor operation without active control at nominal power.
4. static power conversion.
5. 10,000 hours of autonomous operation.
6. a reduction of temperature no greater than 8-10°C for 5 years of operation, and
7. a thermal power range scalable from 300 kWth to 300 MWth.

The GAMMA reactor system is designed to provide electricity for either remote villages or underwater operations. The output characteristics can be optimized for heating, as well as the production of electricity dependent upon the requirements.

GAMMA Reactor System Operating History

A proof-of-principle reactor system, the GAMMA, completed manufacturing and began testing at the KIAE in 1981. It produces 6.6 kWe at a thermal power of 220 kWth. The system is designed to be able to deliver 28, 110 or 220 volts of electric power. Thermoelectric (TE) power conversion was selected due to its inherent long-term stability and high reliability. The TE power conversion units were based upon the design and test data obtained at KIAE as part of the Romashka space reactor system development during the mid-1960s. The GAMMA system is 6 m diameter by 10 m high. A schematic of the GAMMA reactor system is shown Figure 1.

Preliminary tests on the GAMMA reactor system were completed to ensure the reactor was stable during power transients or from external disturbances such load changes. Overall a large number of experiments were completed on the unit, including investigating the effect of the load on the performance of the TE power conversion and the associated feedback on the reactor. The Russian specialists checked their experimental data against computer calculations to develop an analytical basis.

To present the GAMMA has operated for more than 10,000 hours at nominal power. It has provided the proof-of-principle for the follow-on ELENA reactor system.

GAMMA Reactor System Description

The GAMMA reactor system and power conversion system operate in a pool of water which conductivity removes the waste heat from the system. There is roughly twenty feet of water from the top of the reactor vessel to the top of the water in the pool.

The reactor system uses water as both the primary and secondary coolant. The coolant from the reactor outlet goes directly to the TE power conversion and heat exchanger units. There are a total of twenty-four TE power conversion modules located above the reactor core and are arranged in a circular pattern around the outside of the reactor vessel. The coolant heats the hot-side of the TE power conversion on the inside of the coolant flow path and the TE cold-side is cooled by the pool of water. The coolant is pressurized and does not boil.

There are no pumps in the primarily coolant loop, rather the heat is transfer by natural circulation. Initially there was some problem with air stagnation at the top of the TE power conversion-to-heat exchanger units, but the Russian technical specialists believe they have solved this problem.

The reactor is fueled by uranium-dioxide (UO_2) enriched to ~20% U-235. The enrichment level was chosen to ensure it was below the level of concern for nonproliferation. The power density in the reactor core is very low. The system is designed for 10 years of operation without refueling.

ELENA Reactor System

The reactor system was named ELENA after the first remote site that the system was to be operated. The ELENA system has not been built or tested, but the technology is based on the principles and the operation of the GAMMA reactor. It was designed specifically to provide electric power and district heating for remote villages or locations.

The baseline design of the ELENA reactor system is to produce 90 kWe at 3 MWth, although the design can be scaled to produce higher power dependent upon the intended location and use. Of the 90 kWe produced, 20 kWe is used to operate the system and 70 kWe is available to the user. The TE power conversion system has low electrical conversion efficiency, and the waste heat is used for district heating. The electrical power output versus the excess heat for district heating can be optimized for the specific location and use. Table 1 provides a listing of the key parameters for the ELENA reactor.

The reactor thermal power is kept constant and does not vary with the electrical load. There are two options for controlling the electrical power output: 1. use shunt resisters, or 2. to short circuit the TEs. Both of these have been analyzed by the Russians, but no final decision has been made as to which option should be used. They believe the decision should be dependent upon the specific electric loads. Two other options are to attach the third loop to a natural draft cooling tower, or to use it to heat green houses.

Coolant System

The ELENA has three water coolant loops: the primary coolant loop that goes from the reactor to the hot-side of the TE power conversion, the secondary coolant loop which removes the excess heat from the cold-side of the TE power conversion and the third coolant loop which takes the excess heat external to the plant for district heating. The complete reactor system is fabricated from stainless steel. The temperature of the water within the third loop is ~100°C. If the temperature to the heat supply is dropped by 10°C, then the output power of the system doubles. The power level is primarily dependent upon the temperature of the third loop. A schematic of the ELENA system is shown in Figure 2.

The heat is transferred from the reactor core to the power conversion units by natural circulation. The typical operating parameters of the primary coolant loop are 150 to 200 kg/cm^2 pressure and 300 reactor inlet and 330°C outlet temperatures. The secondary coolant loop transfers heat via natural circulation and it serves as a biological shield. The typical operating parameters for the secondary coolant loop are 1 to 2 kg/cm2 pressure and temperature difference of 80 to 95°C. The third coolant loop operates at 3 to 4 kg/cm2 pressure and 70°C to 90°C temperature inlet and outlet.

Power Conversion

The ELENA reactor system is designed with 290 tubular TE power conversion elements within eight power conversion to heat exchanger units placed outside of the top periphery of the core. The GAMMA reactor system TE power conversion system were fabricated within Sukhumi, Georgia but future elements could be fabricated within Russian or the U.S.

The TE elements are made from Bismuth-Tellurium-Selenium. Based upon the testing completed on the GAMMA reactor system the Russian specialists estimate 10% degradation of the performance of the TE power conversion over twenty-five years of operation. Component-level testing of the TE units have been done for up to 150,000 hours in a nonreactor, i.e. nonradiation environment, at Sukhumi and for 11,000 hours as part of the GAMMA reactor system test program. The TE power conversion have been tested to flux levels of up to 10^{19} n/cm^2-sec without significant degradation, where the actual operational flux levels for the ELENA reactor system are anticipated to be 10^5 n/cm^2-sec.

Reactor Description and Operation

The ELENA reactor does not require an operator during nominal power operation during the lifetime of the plant. Operators are required for assembly, startup and to begin nominal operation. There are no valves or mechanical parts which require maintenance over the operation of the plant. There is no requirement for refueling of the system over the twenty-five years of operation.

Once operational the ELENA depends upon natural processes to maintain the reactor power without the actuation of control rods. The control and safety system, including the control rods, control drive mechanisms, sensors, etc. are used only for the startup of the reactor, or for times that the reactor may scram and have to be shutdown. The control and safety are designed to fail safe.

The reactor startup is done by measuring the neutron flux and calculating the reactor period. The reactor outlet temperature and the pressure in the coolant loop will be monitored, but do not provide feedback through the control loop during startup. Startup is done by an on-site operator who can leave the site once steady-state power has been obtained. The plan was to have a single operator at a control site where the operation of roughly six of these power systems at different remote sites would provide operational data. If there were a problem, the information would be sent to the operator. To operate the poison rods are pulled completely from the core, and are never inserted during nominal operation. The poison rods are available for scramming the reactor if their is a problem.

The plant emergency protection system would monitor the plant during operation, and would be capable of scramming if the operating parameters were outside specified values. There are six clusters each with twenty poison rods. Four out of the six clusters can shut the reactor down. A signal is sent from the plant protection system to scram the rods and they are driven in by springs. If their is a failure in the electrical circuitry the rods are dropped into the core by gravity. If the system does scram, an operator is required on-site to restart the reactor. The monitoring system uses the neutron power, the pressure, and temperature. There are three measurement channels for each of the above parameters. If two of the three channels exceed specified values the reactor will be scrammed.

The reactor core has standard Russian VVER-1000 fuel elements with UO^2 fuel clad in zircalloy. The reactor is designed with a negative temperature coefficient over the complete range of operation. The fuel burnup is compensated by slight decreases in the coolant temperature over the operating lifetime and the burnup of the gadolinium burnable poison. Therefore, the initial amount of excess reactivity can be low.

ELENA Size/Mass Characteristics and Decommissioning

The mass of the ELENA system assembled is 213,145 kgs (235 tons), or 147,841 kgs (163 tons) dry weight. The mass of the coolant in the first loop is 3628 kgs (4 tons), and the mass of the coolant in the secondary loop is 61,676 kgs (68 tons). The reactor system can be broken into two parts for shipment. It is possible to fuel the system on-site, thereby eliminating problems associated with shipping a fueled reactor. The vessel head of the system can be removed. Some on-site welding would be required. The plant is ~5 meters in diameter with a height of 10 meters. It does not require a large work force to assembly and begin operation of the plant.

The unit can be decommissioned and moved one to 1.5 months after it has been shutdown. The UO_2 fuel can removed and put into a shipping container a bundle at a time. The diameter of each fuel bundle is 7.0 cm and the length is 2 m. There are two options in decommissioning the stainless steel balance-of-plant: 1. it can remain in place for two years, be disassembled and packaged according to safety procedures, or 2. disassembled soon shutdown with more stringent safety procedures.

Safety

The ELENA was designed after the Chernobyl accident and therefore safety was considered of utmost importance in the design of this system. The Russian technical specialists have analyzed some potential accident scenarios and have not identified any that would result in the release of fission products or fuel melting. Because the specific power in the active core is so low, 7 kWth/liter, the Russian specialists are not concerned about a loss of coolant accident. The Russian specialists believe that natural circulation is adequate to cool and maintain the integrity of the core under any conditions. The primary coolant loop is completely contained within the secondary coolant loop and provides a secondary barrier. If the ELENA system is placed approximately 20 to 25 meters underground there would be no increase in radiation at the ground level while the plant was operating.

Technology Transfer Program

If the safety and performance claims for the ELENA concept can be confirmed and independently validated then it could prove to be a valuable district heating or desalination and electric power supply for many remove villages, industrial and scientific sites throughout the world. A practical and realistic approach to accomplishing this independent validation is to certify a standard design with the U.S. Nuclear Regulatory Committee (NRC). It is necessary to establish a U.S. industrial partner with Russia to proceed with an application for NRC certification application.

Key to developing interests and implementing the initial evaluations is confirming a market potential that would justify the investment. A three step approach is underway: 1) assess the worldwide potential for using the ELENA concept in various remote sites. China alone has 30,000 villages that could benefit if a suitable system were available, 2). conduct the technical and cost assessments, possibly through a join DOE laboratory, Russian institute and U.S. industrial partnership, and 3). if the initial efforts prove positive for U.S. commercial interest a plan of supply and certification could be implemented.

Conclusions

The GAMMA system is designed to provide power for primarily underwater applications and the Elena reactor system can provide power for remote sites. The GAMMA system has been tested at the KIAE and the operating parameters have been verified. Further study of these systems is recommended for site specific applications. In particular, further analysis should be completed on site requirements, optimization of the plants to produce electrical power versus local space heating completion of a plan to fabricate and assemble the system at a remote site, and a complete safety assessment consistent with the U.S. NRC requirements.

TABLE 1: ELENA Reactor System Design Parameters

Lifetime	25 years without refueling		
Thermal Power	3 MWth		
Electric Power	90 kWe		
Plant Operating Power	20 kWe		
Fuel Material	UO^2		
Fuel Enrichment	<20% U-235		
Fuel Mass	160-190 kgs		
Maximum Operating Temperature of UO2	<400°C		
Maximum Temperature of UO2 Under Accident Conditions	<1000°C		
Reactivity Compensation	Negative temperature coefficient and Gd burnable poison		
Reactor Power Density	7 kWth/liter		
Plant Protection System	Six clusters with 20 poisons rods each for scram only	Four out of six can shut the reactor down	
Monitoring System	Neutron power, pressure and temperature	3 channels per parameter	
System Material	Similar to U.S. ~316 SS		
Number of coolant loops	3		
Coolant	Water		
Loop 1*: Pressure/Temperature/ Volume of Coolant	150 to 200 kg/cm^2	300 and 330°C	4 tons
Loop 2*: Pressure/Temperature/ Volume of Coolant	1 to 2 kg/cm^2	80 to 95°C	68 tons
Loop 3*: Pressure/Temperature/ Volume of Coolant	3 to 4 kg/cm^2	90°C and 70°C	
Power Conversion	Bi-Te-Se Thermoelectric Elements		
Number of Power Conversion Units	290 tubular TE elements within 8 heat exchanger units		
Coolant Circulation	National circulation in Loops 1 and 2. Loop 3 is pumped for local space heating.		
Cost	Dependent upon location		

*The loop operating parameters will change dependent upon the balance between required electrical power output and local space heating.

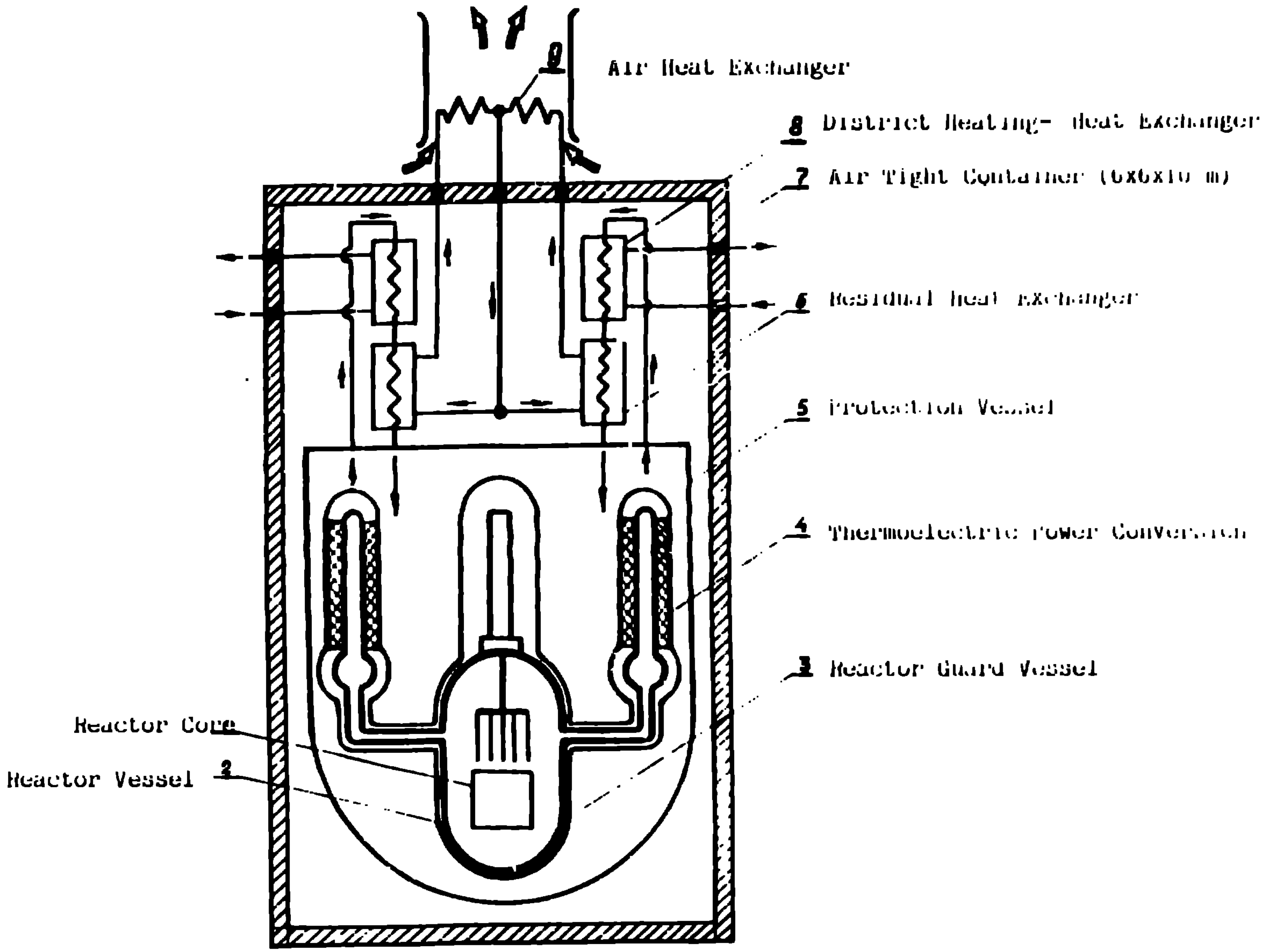

Figure 1: GAMMA Reactor System Schematic.

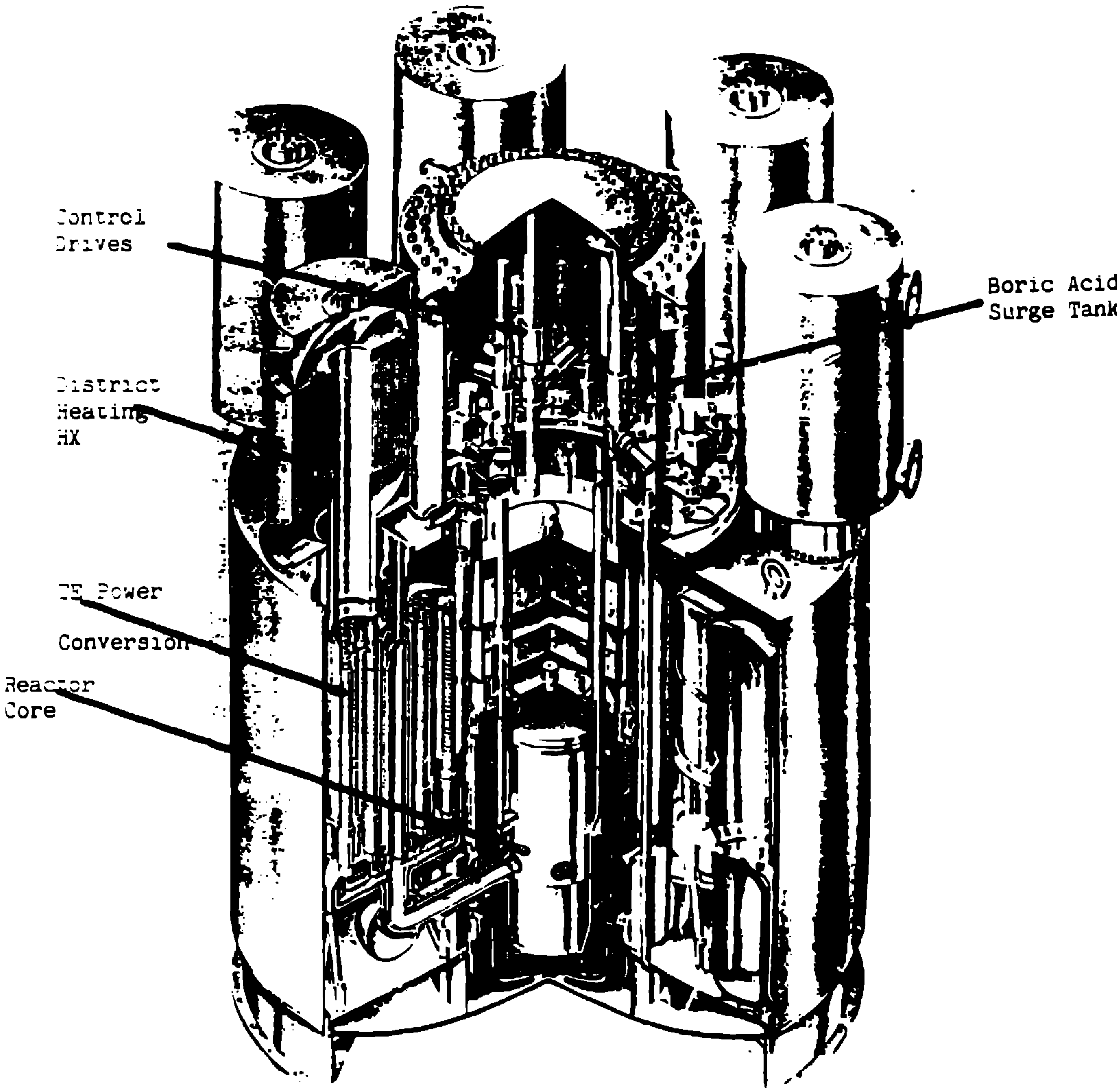

Figure 2: ELENA Reactor System Schematic.